Adaptive Route Optimization for Operations – Concept of Operations

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16. Abstract

This document is a concept of operations for developing a snowplow adaptive route optimization (ARO) solution. The information in this concept of operations supports systems engineering for creating an ARO system or tool that incorporates real-time and historic data for maintenance and operations personnel to use during adverse winter weather. State departments of transportation currently spend more than $2 billion per year on snow and ice control and more than $5 billion per year on repairs due to snow and ice operations, chemical use, and wear. Given these costs, even minor improvements to snowplow routing can produce savings through reduced staff time, material use, and waste. This concept of operations describes current snowplow routing technologies and practices, the need for changes, the concept for ARO, application scenarios, impacts on systems and organizations, and advantages and limitations.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

ARO	adaptive route optimization
ARP	arc-routing problem
ATMS	advanced traffic management system
AVL	automatic vehicle location
CARP	capacitated arc-routing problem
ConOps	concept of operations
COTS	commercial off-the-shelf
DOT	department of transportation
ESS	environmental sensor station
FHWA	Federal Highway Administration
GPS	global positioning system
I–25	Interstate 25
IMO	integrated mobile observation
IOO	infrastructure owner-operator
MDSS	maintenance decision support system
NWS	National Weather Service
RWIS	road weather information system
TMC	traffic management center

EXECUTIVE SUMMARY

Adverse weather has a measurable impact on roadway safety, mobility, and productivity. It increases driving risks and travel times, and creates operational challenges for transportation agencies. There were more than 241,000 injuries and 6,000 fatalities on U.S. roadways with adverse weather conditions as a contributing factor in 2019. State departments of transportation (DOTs) spend over $2 billion per year on snow and ice control. They spend over $5 billion per year on repairs due to snow and ice operations, chemical use, and wear.

Operations to restore service on roads affected by winter weather conditions may include anti-icing to postpone frozen precipitation on the roadways, plowing to remove snow and ice from roadways, and using de-icing material to improve the pavement state. Each DOT has its own goals and challenges in getting roadways back to pre-storm levels of service. Planning and routing for winter maintenance generally builds on past practice and results, conditioned by the profile of the storm.

Adaptive route optimization (ARO) is a method of dynamically and effectively routing winter maintenance vehicles across all segments of a road network to meet an agency's maintenance objectives, subject to weather conditions, traffic, and resource constraints. ARO can enable agencies to respond more quickly and efficiently than is possible with current routing systems to changing storm conditions, resource constraints, and service expectations. It has the potential to restore pavement conditions faster, reducing weather-related risk and improving mobility. Winter maintenance can be expensive and use up a big part of agency budgets, so any gains in efficiency can produce savings through more efficient material usage. Agencies using ARO can develop more efficient routing plans that makes the most use of staff time, materials, and equipment.

The ARO system will incorporate real-time and historic data in a snowplow routing solution for DOT maintenance and operations to use during adverse winter weather. The solution will support a strategic view for maintenance planning and a tactical view for real-time operations. Dashboards will be provided for users including managers, maintenance supervisors, and drivers.

The ARO system will consider level-of-service goals, route and segment priorities, cycle time expectations, and current and forecast roadway conditions in route optimization. Current (near real-time) conditions to be addressed include atmospheric weather, road weather, incidents, work zones, and traffic volume (or demand). Forecast conditions to be considered will at minimum include weather and road weather conditions, and may include other traffic and operational predictions. Routes will further consider historical crash data, recurring problem areas, and weather-related experience for their routing risk implications. Routing will consider constraints specific to snowplowing operations such as access to fuel and material depots, turnarounds, U-turns, intersection snow clearance, and driver deadheading.

The ARO system will enable DOTs to better respond to changing winter weather events and circumstances. Scenarios in which ARO can improve agency responses include, for example:

- Optimizing snowplow routes with reallocation of plowing resources among maintenance sheds and regions.

- Adaptively optimizing routes to changing weather conditions while treatment cycles are underway.
- Tactically re-optimizing snowplow patrols around active incident sites and the resulting congestion.

A successful ARO system implementation would lead to faster restoration of clear pavement, safer roadway conditions for the traveling public, and improved mobility under winter driving conditions. As a related benefit, an ARO implementation needs more complete and timely views of operations and winter maintenance activities across the road network. This will improve awareness within and across the transportation agency, and will enable timelier and more effective communications with the public.

Within the agency's operations, ARO can improve human and equipment resource utilization in winter operations. The improved routing could reduce the total route miles and deadheading, which in turn would improve operator satisfaction and morale. Better knowledge of and planning for storm conditions and routing could potentially result in less treatment material usage (relative to non-optimized routes in the absence of an MDSS) and reduced environmental load.

CHAPTER 1. INTRODUCTION

IDENTIFICATION

This document is the concept of operations (ConOps) for adaptive route optimization (ARO) for operations.

DOCUMENT OVERVIEW

The structure of this document is consistent with the outline of a ConOps described in *IEEE 1362-1998 - IEEE Guide for Information Technology – System Definition – Concept of Operations (ConOps) Document* (Institute of Electrical and Electronics Engineers 1998). Some sections have been enhanced to provide more details than are described in the standard, and titles of some sections have been edited to capture that enhancement.

The organization of the ConOps is as follows:

Chapter 1 introduces the background and purpose of the ARO project and this report.

Chapter 2 describes the current state of winter operations, routing, and technology.

Chapter 3 describes the needs for change in the current state of operations and technology.

Chapter 4 describes concepts for ARO.

Chapter 5 identifies and describes use cases for ARO in infrastructure owner-operator (IOO) operations.

Chapter 6 describes the potential impacts of ARO in IOO operations, organization, and system deployment.

Chapter 7 describes the potential advantages, opportunities, disadvantages, and risks in ARO deployment.

References identifies references relative to ARO and this ConOps.

BACKGROUND

Adverse weather has a measurable impact on roadway safety, mobility, and productivity. It increases driving risks and travel times and creates operational challenges for transportation agencies. In 2019 there were more than 241,000 injuries and 6,000 fatalities on U.S. roadways with adverse weather conditions as a contributing factor.[1] Although rainstorms are more common, winter weather events have a bigger impact on agency costs to maintain roadway service levels. State departments of transportation (DOT) spend more than $2 billion per year on

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[1] National Center for Statistics and Analysis, *Traffic Safety Facts 2019: A Compilation of Motor Vehicle Crash Data*, DOT HS 813 141 (National Highway Traffic Safety Administration: August 2021).

snow and ice control. They spend over $5 billion per year on repairs due to snow and ice operations, chemical use, and wear.[2]

Road weather information, such as pavement temperatures and condition, can help reduce the operational impacts of adverse winter weather conditions. Timely and accurate traveler information can change driving patterns to reduce the risk of crashes, injuries, and fatalities. DOT winter operations and maintenance staff use pavement condition, temperatures, and precipitation data to plan how to restore roads to levels of service commensurate with traffic volumes and speeds. These operations generally will include anti-icing to postpone frozen precipitation on the roadways, plowing to remove snow and ice from roadways, and using de-icing material to improve the pavement state.

Each DOT has its own goals and challenges in getting roadways back to pre-storm levels of service. In general, maintenance planning and routing builds on past practice and results, conditioned by the profile of the storm. Results for the road network as a whole depend on setting the safety and mobility goals and routing the available vehicles in the maintenance fleet. Results for a specific segment of roadway depend on factors such as the type of storm and precipitation, timing of operations, and the type of treatment. The time to plow and treat all road lanes on a route can be affected by the truck's material capacity, location of maintenance sheds, events on the roadway, changing winter storm conditions, traffic, and staff shift changes.

Changes in weather patterns, road network conditions, agency resources, and public expectations are challenging past practices for planning and routing. Intense weather events—whether winter snow and icing, hurricanes, or droughts and dust storms—are becoming more frequent. Traffic in urban areas and along interstate corridors is more congested even while lane miles increase. Agencies continue to struggle with budgets and staffing to keep up with increased needs for maintenance resources. Public perception focuses more on extreme events, where expectations may not have been fully met, than regular consistent service. These factors create an opportunity to improve safety and mobility on roads subject to winter weather through better vehicle routing. Operators and maintenance supervisors understand the need to improve current practices. However, route optimization is a complex science. Routing for winter maintenance needs research into models and methods to improve the state of its practice.

The objective of this research in ARO for operations is to create systems engineering documentation for an ARO system or tool that incorporates real-time and historic data for DOT maintenance and operations personnel to use during adverse winter weather. This will be accomplished based on current practices; DOT experiences; and gaps found in a literature review, technology scan, and interviews of DOT early deployers. End users for this system include snowplow operators, maintenance supervisors and management, transportation management center (TMC) personnel, public information office staff, and emergency management responders.

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[2] Clear Roads Pooled Fund, *Benefit-Cost of Various Winter Maintenance Strategies* (September 2015).

CHAPTER 2. CURRENT STATE

This chapter describes the current state of winter maintenance routing practices and impacts. It describes the larger context of winter maintenance operations to show how routing fits with other activities. It also describes the physical and informational components, stakeholders, modes of operation, common routing practices, and technologies currently in use.

BACKGROUND, OBJECTIVES, AND SCOPE

Winter Maintenance Overview

Winter storms can create challenging driving conditions across large areas of a road network. State and local transportation agencies work together within their jurisdictions to ensure that safety and mobility across the network are preserved and restored during and after the storms. Their planning and activities are based on winter maintenance technologies and practices that have matured over decades of development and operating experience. Specific maintenance activities during a storm, nonetheless, depend on the characteristics and timing of each storm.

The full scope of winter maintenance processes starts before the season with setting maintenance objectives. Human, capital, and material resource needs (e.g., drivers, trucks, and materials) are estimated, acquired, and allocated to maintenance facilities across the agency's area of service for the coming winter season. Routing and treatment plans based on the maintenance objectives and resource plans are set up for typical storm conditions. As the season starts, weather conditions are monitored for approaching storms. Each storm is met with treatment and plowing activities tailored to weather, pavement, and traffic conditions based on the timing and severity of the storm. Figure 1 illustrates the high-level processes for winter maintenance routing.[3]

The condition of roads during and after winter storms directly impacts public safety and mobility. Objectives for an agency's winter maintenance activities reflect the importance of preserving and restoring pavement to pre-storm conditions. Although maintenance goals vary among agencies, the intent is generally to clear roads of snow and ice as quickly as possible. Roads with higher traffic volumes will generally get higher priority and be cleared more quickly. Roadways with higher safety risks or providing few alternative routes for public travel may also get higher priorities. Maintenance activities might also be measured by how effectively they use human, capital, and material resources. Routing should address these objectives and priorities and has a direct impact on meeting them.

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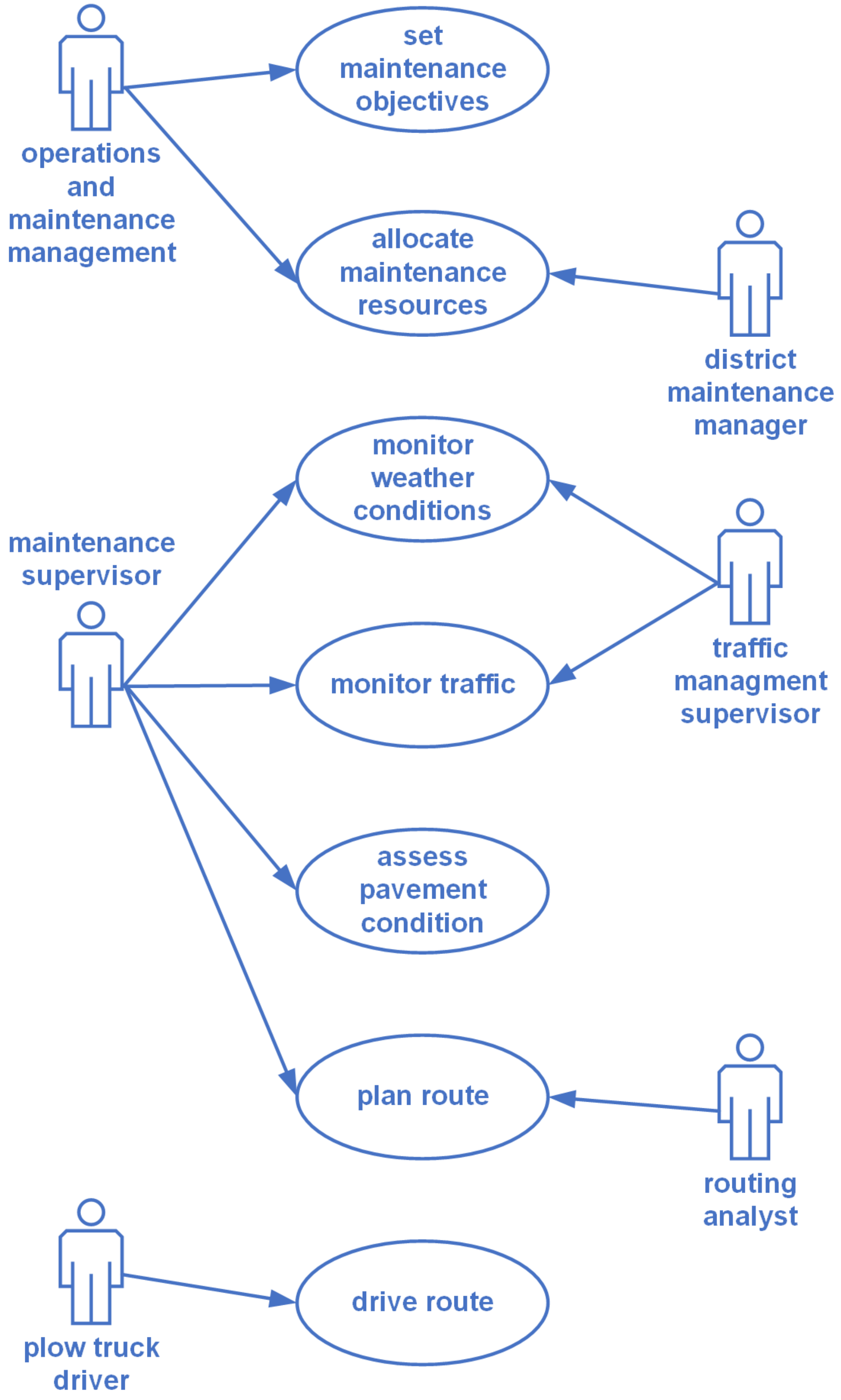
[3] User designations and associated use cases are examples and may not apply to any particular State or local transportation agency.



Source: Federal Highway Administration (FHWA).

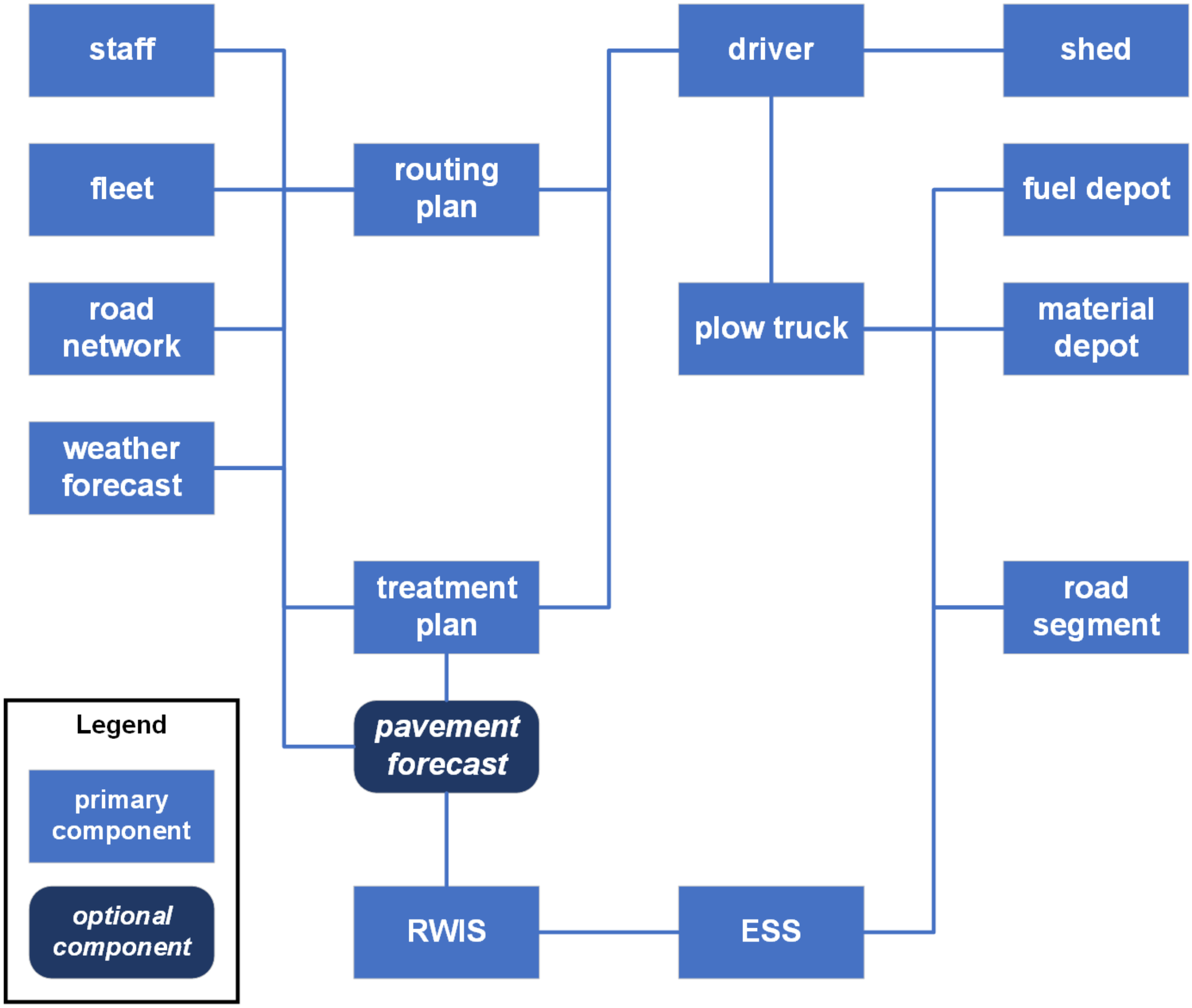
Figure 1. Diagram. Current state winter maintenance routing use cases.

Winter maintenance during a storm uses significant resources over a relatively short time. Planning for maintenance considers equipment, personnel, and material needs that may vary over the winter season and across the agency's area of operations. The agency's treatment capacity is directly driven by the number and capacities of maintenance vehicles in the fleet. Drivers must be available for each vehicle to be deployed. Maintenance depots, whether belonging to the agency or to a contractor, must be supplied with fuel and materials used in treatment and plowing. Routing for maintenance must consider all of these factors.

As winter approaches, maintenance personnel monitor weather conditions for approaching storms. Agencies may use National Weather Service (NWS) forecasts and alerts and may supplement them with in-house or contracted services focused on forecasts for atmospheric weather and pavement condition. Forecast details of precipitation type, rate, location, and timing factor into the treatment plans and routing of maintenance vehicles across the road network. These plans may change as a storm approaches and near-term forecasts change. Treatments and routing may change yet again as the storm moves through the service area and observed conditions on the ground differ from the forecasts.

The winter maintenance processes all interact with a set of system components, illustrated in figure 2. The following concepts are common to most winter maintenance activities and systems:

- The staff represents the human resources for planning and executing winter maintenance operations.
- The fleet represents the capital resources with which winter maintenance operations will be conducted.
- The road network represents the geophysical extent of the roadways for which the agency has winter maintenance responsibilities.
- A weather forecast provides a view of impending weather conditions for which the agency needs to plan winter maintenance operations.
- A routing plan describes the distribution of the maintenance fleet and drivers (from among the staff) across the road network as needed to respond to the weather forecast.
- The treatment plan provides instructions for plowing and distribution of pavement treatment materials on road segments within the network. Materials could include anti-icing chemicals and abrasives that can boost vehicle traction on ice and snow.
- A treatment plan may be informed by environmental sensor station (ESS) observations of pavement and weather conditions along roadways, collected by a road weather information system (RWIS).
- Road segments are various sections of pavement over which winter maintenance operations take place. They may vary in the number of lanes, pavement material, elevation above grade (if a bridge or overpass), pavement condition, and in planned treatment. A route is a collection of road segments along which winter maintenance will occur.
- A maintenance shed is a facility from which drivers typically start and end their routes.
- Depots are locations where fuel and treatment materials are stored for use in maintenance operations. A maintenance shed may also be a fuel or material depot.



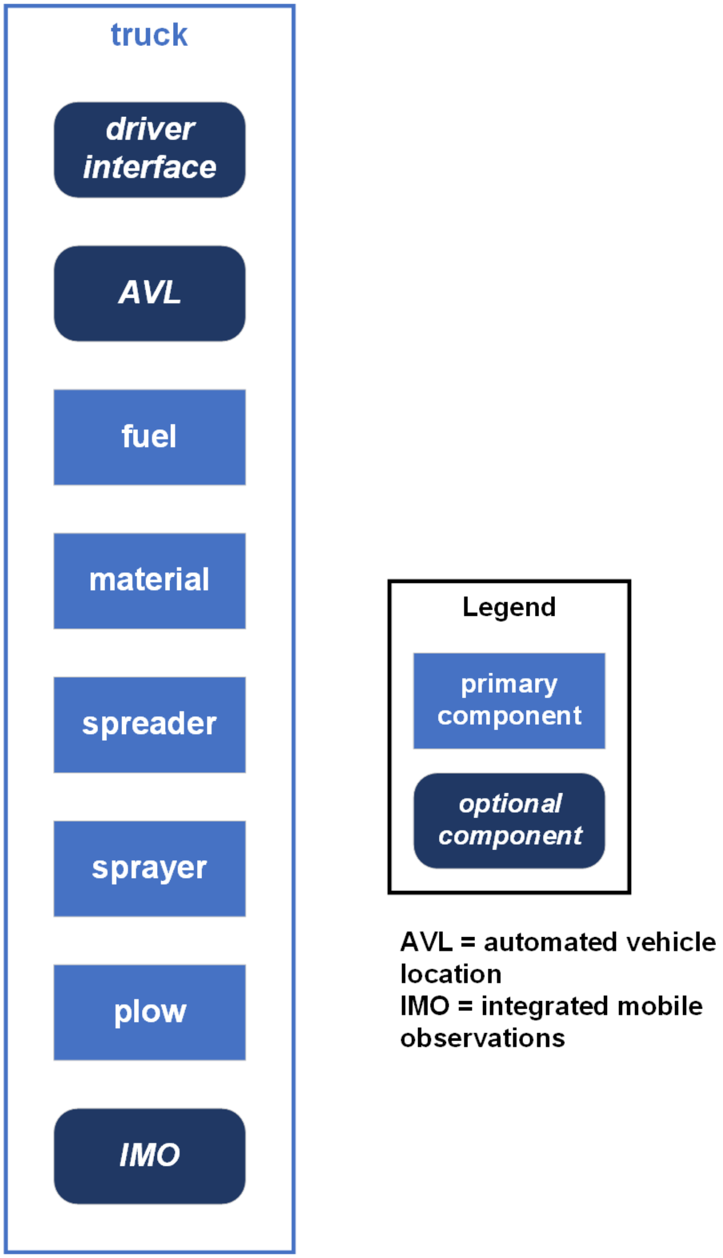
ESS = environmental sensor station. RWIS = road weather information system.

Source: FHWA.

Figure 2. Diagram. Current state winter maintenance system components.

The typical winter maintenance vehicle is a truck configured with plowing and treatment equipment. As shown in figure 3, the truck may be equipped with the following equipment for monitoring road conditions and maintenance operations:

- A snowplow truck will have a snowplow, which might be any of several configurations.
- The truck is likely to have a bin and spreader for solid material or a tank and sprayer for liquid chemicals.
- The truck may have an automated vehicle location (AVL) system and a driver interface for sending information about operations back to a maintenance management system.
- The truck may have sensors for integrated mobile observations (IMO) of pavement and weather conditions.



AVL = automated vehicle location
IMO = integrated mobile observations

Source: FHWA.

Figure 3. Diagram. Current state winter maintenance system plow truck detail.

Routing Optimization Objectives

Route optimization is a process for determining the most effective route that meets the service objectives. Route optimization also looks at how to improve routing to reduce costs or cycle times beyond current expectations. Typical agency winter maintenance routes are based on service objectives shared among the public and the agency, extent of network, agency resources (e.g., equipment, material storage, and labor), and operations goals (e.g., cycle times or deadhead). These existing routes may meet public and agency needs for a network that is stable and not growing or adding new lanes. Routes may be modified to add road segments or lanes, change material storage locations, or add equipment with new capabilities (e.g., tow plows[4]) or revised service goals.

Route optimization can be used to solve routing problems for snowplows, handling cellular phone data, and package delivery. Route review tools may be used to visualize a route, track important route characteristics, such as mileage and cycle time, and make manual route revisions. Route optimization tools generate entirely new routes based on mathematical algorithms (Dowds et al. 2016). The optimization process uses multiple objectives to arrive at a solution. In terms of winter maintenance, agencies could, for example, find solutions that reduce driver hours, fuel costs, cycle times, or material usage.

Route optimization for winter maintenance is considered static, meaning that routes do not change without manual intervention once the process has been applied. The routes use expected conditions such as storm intensity, traffic patterns, truck availability, and traffic conditions. Static route optimization does not account for extreme weather events or unexpected issues that may arise during winter storms, although it is an advancement over a simple shortest-path routing.

STAKEHOLDERS

Figure 1 shows stakeholders that may be involved in route optimization. Their interests in winter maintenance provide a basis for and execution of the optimized routes.

An agency's operations and maintenance management sets objectives and manages resources for winter maintenance, alongside other operations and maintenance goals. These stakeholders have a perspective across an agency's entire area of operations and road network. They may coordinate with management in other agencies to ensure the public is served in urban and rural settings, across all roadway functional classifications, and across jurisdictions. They coordinate activities and resources across districts within their own agency.

District maintenance managers and engineers manage winter maintenance activities and resources within their areas of service. They also coordinate with management in other agencies to ensure the public is served in urban and rural settings, across all roadway functional classifications, and across jurisdictional boundaries.

Maintenance supervisors oversee winter maintenance activities undertaken by one or more agency district facilities, alongside other non-seasonal responsibilities. As part of their winter maintenance role, they monitor weather conditions, traffic conditions, and timing of operations; assess pavement conditions; and communicate with drivers in route. They also manage and monitor resources at maintenance facilities, working with district managers to ensure adequate staffing, vehicles, and treatment materials throughout the winter.

Traffic management supervisors and operators at some agencies may support winter maintenance in monitoring weather and traffic conditions. Operators may receive near real-time reports of roadway conditions through 511 or 911 phone calls or through internet-based traffic information

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[4] Tow plows are steerable trailers usually pulled behind a dual-axle snowplow.

applications. Reports that may affect maintenance activities can be passed to maintenance supervisors.

Routing analysts may assist maintenance supervisors in setting up or optimizing winter maintenance routes. Most agencies use static routes established through years of practice. Routes are typically not changed unless a road network or maintenance objective changes have led to a review or optimization process. As such, the routing analyst role might be filled by a maintenance supervisor or a contractor specifically brought in to recommend route improvements.

Plow truck drivers are the on-the-ground implementers of the routing plan. They get the routing and treatment plans at the start of the maintenance cycles. They make real-time routing decisions based on road and traffic conditions in communication with the supervisors to work around emerging situations and complete the plowing and treatment plans. They submit maintenance reports at the end of each cycle or shift.

MODES OF OPERATION

Modes of operation identify related functional capabilities of a system based on a setting or context. For winter maintenance routing, modes of operation currently include static routing, optimized static routing, and adaptive (in-route) routing. Most agencies use static routing for winter maintenance. Routes are based on the available maintenance vehicles and facilities in a service area or district. Drivers are typically assigned to a set of routes to be covered in each storm and cycle over the winter season.

Optimized static routing optimizes the static routes to one or a few particular routing constraints—for example, fastest clearance times or fewest miles driven. An optimized routing plan would only be revised when the road network to be covered or the optimization parameters have changed.

Adaptive routing makes changes to a static route for exceptional circumstances in weather or traffic while drivers are in route. A driver might become aware of changing circumstances (e.g., an incident blocking the planned route) that require rerouting and then notify the maintenance supervisor of the changed plan. Alternatively, a changing weather forecast might suggest that a planned route be canceled. New routes are adapted to the immediate circumstance rather than remaining committed to the pre-optimized routes.

CURRENT SYSTEMS

Agency Practices and Experience

The authors conducted interviews with three State DOTs and two local agencies that have considered or are using route optimization.[5] The interviews identified the state of the art,

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[5] Hawkins, N., and J. Dong. 2021. *Literature Review, Technology Scan, and Early Adopter Interviews: Adaptive Route Optimization*. FHWA-HOP-21-098. Federal Highway Administration.

challenges, gaps, and opportunities to enhance ARO capabilities. These agencies represented a range of snowplow fleet sizes, geographic locations, and winter climate.

All interviewed agencies have a set of static routes. The agencies make route adjustments pre-storm to account for issues such as staff being sick or late, or equipment being out of service. During the storm, supervisors and operators might change material application rates and routes based on weather and road conditions. Most districts, counties, or zones operate independently and do not typically cross boundaries. Some agencies do not own snowplows so they compensate the counties to plow State roads.

Three counties in Wisconsin conducted route optimization by combining State and county roads, which resulted in significant improvements in efficiency. However, keeping track of salt use by roadway requires counties to equip their trucks with AVL or global positioning system (GPS) equipment for location tracking, material monitoring, and communications to transmit the information back to the office. Not all Wisconsin counties have this equipment, so the practice is not widely deployed. Ohio DOT looked at ways to enable better routing by removing district borders. When severe winter storms approach, Ohio DOT ignores district borders, enabling resources to be routed across districts. For example, District 3 shares its resources if District 12 near Erie is struggling to keep up with a storm.

Route planning works alongside treatment planning in winter maintenance processes. Maintenance decision support systems (MDSS) may be used along with information from private weather service providers for treatment recommendations. Agencies are also considering opportunities to share roadway surface data with these services. For example, the City of West Des Moines, Iowa, has four mobile observation units mounted on snowplows to collect and transmit data on road surface state, friction, and temperature. The devices are currently used to capture road weather conditions on arterials and share this information with MDSS. The city also has a project starting in winter 2021 to adjust material spreader rates based on MDSS application recommendations on arterials.

Use of Weather Forecasts

All interviewed agencies work with a weather service provider to get atmospheric and road weather forecasts that support route planning. Although the routes are predetermined, the staffing, selection of routes, and treatment options are adjusted based on the weather forecast. For example, Wisconsin DOT helped counties set up different routing scenarios using a route optimization program that helps schedule staff and overnight crews. In particular, Milwaukee County developed routing and equipment scenarios that describe everything from the deployment of a single truck to full fleet deployment based on graduated levels of winter storm impact. Scenarios are selected in response to weather, crew availability, and traffic conditions.

Impact of Traffic Events

Interviewed agencies noted that snowplow operators generally stay on their assigned routes. However, operators are typically on their own and are encouraged to make safe, independent decisions when routing around unexpected issues. Agencies also try to schedule their work to apply materials or plow roads ahead of peak-hour traffic or major shift changes at factories.

In Wisconsin, disruptions are handled through county management hubs, with some urban counties having pre-set alternative routing scenarios. North Dakota DOT has one traffic coordinator during winter storms to support operator decisions because there is currently no State TMC. Ohio DOT relies on its TMC in Columbus to monitor traffic conditions and potential issues. TMC staff communicate with snowplow supervisors, highway patrol, and local sheriffs when major issues impact winter operations. Dense urban areas tend to have more issues, so the cities of West Des Moines, Iowa, and Pittsburgh, Pennsylvania, both mentioned empowering their operators to determine a safe path around obstacles and to use their judgement as to when communication with their supervisors is needed. Agencies also noted efforts to avoid peak-hour volumes, especially in urban settings. Ohio DOT noted that it tries to get materials applied ahead of shift changes at major factories. West Des Moines tries to clear its major arterials prior to 6 a.m. and before 4 p.m. to avoid delays in rush-hour traffic.

Communications and Rerouting

The interviewed agencies each use two-way radio systems for communication between supervisors and operators. Of the two agencies that have trucks equipped to support MDSS, neither system's in-vehicle units include a display screen. Pittsburgh uses in-cab turn-by-turn directions to support operator routing and any rerouting when necessary. Getting crews to accept this new technology was not automatic and required supervisor champions to help out their peers. Seasoned operators started to appreciate the in-cab directions when working in unfamiliar areas of the city. Temporary and new drivers seem to appreciate the in-cab directions, especially at night.

Adapting Planned Routes

No specific concerns with adapting planned routes were noted among the State DOTs interviewed. They can use city or county roads for rerouting as needed. Pittsburgh, however, is an older city with a variety of roadway widths and steep grades. Its winter operations strategy relies on a fleet of trucks ranging from large tandem-axle trucks to pickup trucks for the narrowest of roadways. The city noted that matching truck sizes to roadway widths would be a major consideration for any future ARO to be applied successfully.

Performance Goals

All agencies interviewed have performance goals, but not all track them. The performance goals the agencies noted are based on targeted pavement conditions, cycle time, and speed recovery, as shown in table 1.

Pavement condition describes what the roads should look like after the snow and ice control operations are completed. For example, West Des Moines has procedures that identifies performance outcomes like mostly bare pavement on the arterials and some snowpack remaining on the residential roads.

Table 1. Winter maintenance performance measures and goals by agency.

Agency	Performance Measure	Performance Goal
Ohio DOT	Speed recovery	Regain normal speeds within 2 hours after precipitation ends and wind speed drops below 15 miles per hour
Wisconsin DOT	Cycle time	Maximum cycle time is 3 hours for State highways and 2½ hours for interstates
North Dakota DOT	Speed recovery	Currently set at 85 percent normal speed
City of Pittsburgh, Pennsylvania	Coverage	Reach every street segment, which can take 12 hours
City of West Des Moines, Iowa	Pavement conditions	Keep major arterials open all the time (i.e., mostly bare)

DOT = department of transportation.

Cycle time measures how long it takes to service all lanes of a road segment along a planned route one time. For example, Wisconsin DOT requires a maximum cycle time of 3 hours on State highways and 2½ hours for interstates. It has also been pushing for a minimum cycle time of 2 hours to allow enough time for rock salt treatments to melt. That is to say, interstates should be serviced every 2–2½ hours, while State highways should be serviced every 2–3 hours.

Speed recovery has become a popular performance measure in recent years. For example, North Dakota DOT measures traffic speeds with microwave sensors and loop detectors. There are 16 active sensor sites (eight districts with two sensor sites per district), and the DOT is looking to add more sites to collect speeds. Ohio DOT uses average speeds from third-party probe data sources. Ohio DOT's goal is to regain normal speed within 2 hours after a storm. In particular, roads should be clear enough for the public to drive at normal speeds after precipitation stops and wind speed drops below 15 miles per hour. Traffic management staff at the DOT track this performance measure.

Maintenance Operations Data

Each of the interviewed agencies collects AVL or GPS data from all or some of their fleets. The three State DOTs and West Des Moines have RWIS stations. The three State DOTs have real-time traffic data.

Route Optimization Practices

All five interviewed agencies have optimized and may have implemented static routes in recent years, as shown in table 2. In general, this requires running an optimization tool and then manually changing the results to ensure practical maneuvers. This iterative process works well with static route optimization. Agencies that have tested or partially implemented static optimized routes have observed savings in fleet travel time. The static route optimization methods have also been used to generate routes for different scenarios, which can be used adaptively based on storm and staffing conditions (Wisconsin DOT), and to determine garage locations (North Dakota DOT and Ohio DOT).

Table 2. Route optimization efforts by agency.

Agency	Route Optimization Tool Used?	Implementation
Ohio DOT	Yes	Development in progress
Wisconsin DOT	Yes	Partially implemented
North Dakota DOT	Yes	Not implemented
City of Pittsburgh, PA	Yes	Some testing with the crew
City of West Des Moines, IA	Yes	Not implemented

DOT = department of transportation. IA = Iowa. PA = Pennsylvania.

Three reasons were given for not implementing the optimized routes:

- **Practicality.** West Des Moines thought the route optimization software output needed quite a bit of modification to account for local operational issues, such as avoiding left turns so as not to leave a row of snow in an intersection. The route optimization effort provided learning points but ultimately did not meet the city's needs.
- **Impact.** North Dakota DOT included both routes and maintenance sheds in the route optimization project. Some small garages would have been eliminated in its optimization results. The impact these closures might have in local rural areas was a big concern at higher levels within the State and prevented implementing the optimized plan. The DOT was able to use the optimization results for reworking some routes at district levels but did not mandate any change.
- **Operator/supervisor resistance.** All the agencies that have partially implemented or are in the process of implementing optimized routes have faced great resistance from crews who are concerned about their jobs and safety. Static route optimization generally reduces the number of routes due to less deadheading compared to the agency's current practice, suggesting fewer operators. Also, route guidance can be seen as a distraction, especially to seasoned drivers on familiar routes. If garage locations are included in the optimization process (as with North Dakota DOT), it could also eliminate some garages.

Off-the-Shelf Routing Tools

Route optimization can be achieved by solving either the node-routing problem or the arc-routing problem (ARP). Node-routing problems, often referred to as vehicle-routing problems, identify customers as nodes in a network and find best routes to visit all customers (i.e., nodes). ARPs find best routes to visit all arcs of a network—road segments, in the winter maintenance case.

Node-routing solutions generate routes for fleets of vehicles to visit nodes for delivery, pickup, or service calls. Given the wide applications in the public and private sectors, the solutions to the node-routing problem are based on research extending back several decades. Algorithms are solving node-routing problems in real time, which leads to implementation in commercial off-the-shelf (COTS) software packages and integration with customized fleet management tools.

ARP, on the other hand, has received less attention. Some examples of ARPs include finding routes for street cleaning and snowplowing, which involves servicing segments of a road network. In some cases, although the demand is located on points (i.e., households), it might be more efficient to aggregate demand to an arc and solve the problem as though it were an ARP. Some examples of such ARPs include postal service and newspaper delivery, meter reading, waste collection, and package delivery in dense urban areas. Very few COTS tools exist specifically for solving an ARP. It is possible to transform an ARP to a node-routing problem and solve it with COTS routing optimization tools. However, problems can arise when trying to incorporate ARP-specific objectives and constraints.

Various COTS tools feature solutions for specific route optimization problems, with most geared toward pickup and delivery route design:

- real-time route modification in which users can insert last-minute orders, adjust stop sequences, and adjust routes if a driver calls in sick. Manual adjustments automatically trigger new routes.
- an optimized route based on users choosing the areas to be driven.
- optimized routes based on real-time traffic conditions.
- a drag-and-drop feature in which users insert new stops on existing routes. Route optimization addresses a large number of constraints, including avoidance zones (i.e., users specify places to avoid, such as high-crime areas and accident-prone intersections) and predictive weather (i.e., automatically updates estimated delivery times to account for poor weather conditions and tells drivers about the weather along their routes).
- an application programming interface that returns a list of traffic incidents and an image of the current traffic situation for a particular area.
- open-source customizable tools for route optimization. With some coding required, a solution can be designed that effectively handles vehicle routing problem constraints.

These types of tools have implemented algorithms that are efficient enough to recalculate new routes in real time in response to changes in demand or traffic conditions. They can be used for both static and adaptive route optimization in the context of pickup and delivery (i.e., solving node-routing problems).

Since snowplow route optimization is an ARP (because it requires vehicles to traverse service arcs instead of visiting service nodes), one can either use tools specifically designed to solve the ARP or convert the ARP to a node-routing problem and then use a COTS product for solving the node-routing problem.

Although static weather and traffic information can be incorporated into the node-routing tools (i.e., the salt demand of each road segment can be dependent on the forecasted storm intensity), RWIS, IMO and sensors, and real-time traffic information have not been incorporated into snowplow route optimization. In addition, recurring problem areas due to weather and historic crash data have been considered in the Colorado DOT network optimization framework by introducing a hazard-map representation (Walsh 2018). Incorporating the hazard-map data into the route optimization requires custom route optimization software. The impact of maintenance shed locations and maintenance resource availability (e.g., equipment, personnel, and materials) can be evaluated using the static route optimization tools by changing the network structure (e.g., different locations of maintenance sheds) or constraints (e.g., the number of trucks available and the length of the shift) and solving the problem for various scenarios.

Academic Literature

Given only a few COTS software tools are available, one might be surprised at the amount of research devoted to formulating and solving snowplow routing problems. The snowplow routing problem has been widely formulated as a capacitated arc-routing problem (CARP) and solved using various exact and heuristic algorithms. This section reviews the algorithms developed for CARP, its variations, and the applications in winter road maintenance routing problems.

Exact algorithms are guaranteed to find the optimal solution for the problem, but it may take a long time. For example, the navigation application on a smartphone may take several minutes to find the absolute optimal route. By contrast, heuristic algorithms do not guarantee an optimal solution, but require shorter computation times. Using the smartphone example, the navigation application can use heuristics to recalculate and change a suggested route based on a wrong turn.

Various exact algorithms have been developed to solve the classical CARP optimally on small networks (Bode and Irnich 2012; Bartolini, Cordeau, and Laporte 2011). However, as in the smartphone example, the exact algorithms cannot always find optimal solutions within a reasonable time. On large-sized networks, it is computationally impractical to find exact solutions. Thus, both metaheuristic[6] and problem-specific heuristic algorithms have been used to find near-optimal solutions (Brandão and Eglese 2008; Mei, Tang, and Yao 2009; Martinelli, Poggi, and Subramanian 2011).

At strategic and tactical levels, route optimization is an integral part of facility location and sector design to determine the best locations for maintenance sheds and assign road network service areas. At an operational level, routes are optimized based on fixed maintenance shed locations and service area. The following operational constraints have been incorporated in the CARP formulation, which are solved using a custom heuristic algorithm:

- **Road-truck dependency.** Snowplow trucks can usually be equipped with either a left-wing or a right-wing plow. Road truck dependency arises when snow and ice must be pushed to one side, either to the median or to the shoulder. Roadways that do not have a wide median need to be serviced by right-wing plow trucks. For roadways with a median wide enough to hold snow, the snow on the inner lane can be pushed to the left (Dong, Zhang, and Yang 2019). Some agencies are using tow plows, which can clear two lanes in one pass and should be assigned to multilane roads.

- **Service continuity.** The service continuity constraint requires connected service links with possible deadhead from the garage to the service beginning node and deadhead from the service end node to the garage (Haghani and Qiao 2002). Deadhead occurs when the truck travels on a road segment without plowing or spreading material. The service continuity constraint requires a truck deadhead only when going to or from the garage

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[6] Metaheuristic algorithms can be applied to a broad range of problems.

rather than in the middle of a route (i.e., the truck cannot skip a few road segments and then plow or treat again). Similarly, Lystlund and Wohlk (2012) solved the service-time-restricted CARP that required the road segment be serviced by the first truck traversal (i.e., deadheading is not allowed before the road is plowed).

- **Road hierarchy.** Some agencies require roads to be plowed and spread in a sequence depending on road prioritization. These road prioritization schemes are usually based on road classification systems or traffic volume. Accordingly, hierarchical routing algorithms have been developed that incorporate a roadway priority constraint requiring that high-priority roads be serviced before low-priority roads (Perrier et al. 2008).

- **Tandem plowing.** Multilane roads sometimes need to be plowed simultaneously by synchronized vehicles in the same direction (Salazar-Aguilar, Langevin, and Laporte 2012). When the entire route requires synchronized service, matching multiple vehicles to a specific route is sufficient to account for synchronization. However, if only a subsection of a route requires synchronized service, inter-route coordination is needed in the optimization model.

In real-time operations, prevailing or forecasted weather conditions and real-time traffic conditions have been considered in adaptive route optimization. Handa, Chapman, and Yao (2005) incorporated a road weather system into its route optimization. The weather system provides road temperature forecast and then yields service-demanding roads based on temperature as inputs for CARP. Tagmouti, Gendreau, and Potvin (2011) considered the dynamic storm moving across the road network. The cost and time for the treatment of road segments changes with the storm movement. Xu et al. (2017) optimized routes based on the benefit of plowing and deadhead costs. The benefit is calculated based on the difference between the total predictive travel time with and without plowing. In particular, the impacts of snow accumulation on roadways (with and without plowing) on travel speed and capacity are used to estimate travel times.

Table 3 summarizes the models that have been proposed to solve CARP in the context of winter road maintenance.

Table 3. Literature on capacitated arc-routing problem for winter operations.

Level	Paper	Objective	Special Constraints
Strategic and tactical	Muyldermans et al. (2002, 2003)	Allocate road segments to maintenance sheds	
	Cai, Liu, and Cao (2009)	Determine maintenance shed locations, allocate road segments to sheds, and design route	
	Jang, Noble, and Hutsel (2010)	Determine maintenance shed locations, allocate road segments to sheds, design route, and schedule fleet	Heterogeneous capacity, fleet size, and road service frequency
Operational	Haghani and Qiao (2001)	Design routes to minimize deadhead distance	Service start time, route duration, time windows, and servicing one or two lanes in a single pass
	Haghani and Qiao (2002)	Design routes to minimize total number of trucks and to minimize deadhead distance	Service continuity
	Omer (2007)	Design routes to minimize total travel distance	
	Tagmouti, Gendreau, and Potvin (2007, 2010)	Design routes to minimize the sum of travel and service costs	Time-dependent service cost
	Perrier, Langevin, and Amaya (2008)	Design routes to minimize the service completion time of the first priority class, then second priority class, etc.	Different service and deadhead speed, class upgrading, road-vehicle dependency, load balance, and turn restrictions
	Salazar-Aguilar, Langevin, and Laporte (2012)	Design routes to minimize the makespan* (i.e., all road segments are serviced within the least possible time)	Road segments with two or more lanes in the same direction are plowed simultaneously by different synchronized vehicles
	Lystlund and Wohlk (2012)	Design routes to minimize the total cost	Road segment is serviced by the first truck traversal (i.e., any deadheading on a road segment must take place at a later time than the time of service)

Table 3. Literature on capacitated arc-routing problem for winter operations. (continuation)

Level	Paper	Objective	Special Constraints
Operational	Dussault et al. (2013)	Design routes to minimize total travel cost	Plowing uphill takes a much longer time than plowing downhill
	Hajibabai et al. (2014)	Design routes to simultaneously minimize the total deadhead travel time and the longest individual truck cycle time	Turn delay and material replenish at salt satellite facilities
	Liu et al. (2014)	Design routes to minimize total travel time	Work shift limit
	Hajibabai and Ouyang (2016)	Design routes to minimize the cost for truck deadheading and maximize the level of service	Material replenishment at salt satellite facilities, uncertain maintenance demand, and uncertain service disruption
	Kinable, van Hoeve, and Smith (2016)	Design routes to minimize the makespan	Heterogeneous capacity and fuel and salt limits
	Quirion-Blais, Langevin, and Trepanier (2017)	Design routes to minimize the makespan and deadhead travel time	Turning restriction, various speed by truck type, road class operations, and road-vehicle dependency
	Gundersen et al. (2017)	Design routes to minimize the total operation time	Precedence relations between the driving lanes and the sidewalks and forbidding or penalizing U-turns
	Dong, Zhang, and Yang (2019)	Design routes to minimize deadhead distance	Heterogeneous capacity, fleet size, road-truck dependency, and road service frequency
Adaptive	Handa, Chapman, and Yao (2005)	Design routes to minimize the total cost	Predicted road temperature and condition
	Tagmouti, Gendreau, and Potvin (2011)	Design route to minimize the sum of service costs and travel costs	Time-dependent service costs
	Xu, Mahmassani, and Alfelor (2017)	Design routes to maximize benefit of plowing (travel time savings with and without plowing) and minimize deadhead	Predictive weather and traffic information

* Makespan is the completion time of the last job.

In terms of solution algorithms, about half of the reviewed papers used problem-specific constructive heuristics. This might be due to the faster computational time these algorithms provide. Given the instances used in these studies are problem specific, it is difficult to compare the effectiveness and efficiency of the algorithms. The heuristic algorithm by its nature does not guarantee global optimum. Instead, it can find a nearly optimal feasible solution much quicker than exact methods.

Related Systems

Routing processes need information about weather conditions, treatment plans, and traffic patterns to develop effective plans for winter maintenance. Static routing plans, even when optimized, presume a limited set of cases and characteristics for each of those data sets. A maintenance supervisor may then need data from other sources to finalize routing for each particular storm.

Weather information and forecast systems are key to winter maintenance activities. Forecasts provide information on when storms may move into a service area and what types and amounts of precipitation may occur. As the storm gets closer and moves into the area, radar and data from RWIS enable supervisors to track its progress and impacts. The following weather information systems could be used to support routing decisions:

- NWS forecasts and alerts
- The agency’s RWIS for observed pavement conditions
- The Federal Highway Administration’s (FHWA’s) Weather Data Environment for observed pavement conditions in other areas being affected by the storm
- Contracted weather services for localization and targeted road weather forecasts

MDSS can be used to plan and track snow removal and treatment based on forecasted storm characteristics. The MDSS provides recommendations on what types and quantities of material to treat roadways for the expected precipitation and on when plowing and treatment need to be applied. The timing of plowing and quantities of materials may then be useful in selecting or adapting routing plans to the characteristics of each storm.

Traffic information may be a consideration in routing plans in urban areas or on high-volume roadways such as interstate highways. A TMC advanced traffic management system (ATMS) may be helpful in providing real-time information on traffic and events that might impact planned routes. Similar information might be obtained from commercial traffic information applications for areas not served by a TMC.

CHAPTER 3. JUSTIFICATION FOR AND NATURE OF CHANGES

JUSTIFICATION FOR CHANGES

Decades of experience and shared practices have established effective winter maintenance of road networks across the United States. Current practices are under pressure, however, and new models are needed to adapt to new events and constraints.

ARO is a method of dynamically and effectively routing winter maintenance vehicles across all segments of a road network to meet an agency's maintenance objectives, subject to weather conditions, traffic, and resource constraints. ARO can enable agencies to respond more quickly and efficiently than is possible with current routing systems to changing storm conditions, resource constraints, and service expectations. It has the potential to restore pavement conditions faster, reducing weather-related risk and improving mobility. Winter maintenance can be expensive and use up a big part of agency budgets, so any gains in efficiency can produce savings through more efficient material usage. Agencies using ARO can develop more efficient routing plans that makes the most use of staff time, materials, and equipment.

As ARO builds on previous concepts for static route optimization, reviewing past routing optimization experience can highlight opportunities. One survey (Dowds et al. 2016) of winter maintenance agencies on snowplow route optimization included responses from 33 State DOTs, 7 Canadian provincial DOTs, 5 local agencies, and 4 identified as "Other." The results were summarized across four types of optimization projects (facility location, service boundaries, fleet size/allocation, and routing) and four optimization methods (manual review, commercially available software, custom software, and external consultant/research team). The findings included:

- Specific to snowplow routing optimization projects, 18 agencies reported using manual methods (including two agencies that also used commercial software and three that also used external consultants). Three used commercially available software. Two used custom software, and nine used an external consultant or research team.

- Successful route optimization relies on close cooperation between modelers and users. Modelers may not fully understand all the operational constraints that affect snowplowing, such as limitations on where vehicles can safely turn around, or size constraints that prevent certain vehicles from servicing narrow roads. Close communication between modelers and winter maintenance experts will improve optimization outputs and limit the need for route revisions.

- Successful route optimization requires a highly accurate representation of the road network created specifically for snowplow route optimization. For example, route optimization frequently requires that individual lanes be represented in the model of the road network. Failure to include features like highway crossovers and safe turnaround locations at the edge of service territory boundaries will result in impractical routing results.

- Computer-generated routes may not be perfect. Successful projects include time to review and revise new routes. Testing routes with supervisors and operators in advance of the winter maintenance season can help to identify potential problem spots and help generate buy-in for new routes.

- AVL systems and GPS are highly complementary to route optimization, route review, and helping drivers with turn-by-turn directions.

Although not currently applied to winter maintenance in the United States, ARO has the potential to improve even optimized static routing. ARO can help agencies use the most efficient routing paths based on actual storm conditions; current traffic; road closures; and currently available equipment, operators, and agency resources.

Moving from static route optimization to the dynamic capabilities of ARO will need to take advantage of access to sources of real-time data. These may include weather, traffic, road weather condition sensors, and event data such as incidents, work zones, and closures.

Route optimization practices are common among companies that deliver goods and services using the transportation and road networks. Static route optimization is the most common, but a transition toward adaptive route optimization is underway, driven by:

- **Shifts in consumer demand.** Consumer demand for package delivery is accelerating along with demands for next day delivery, product tracking, and alerting. U.S. e-commerce shipments were 30 percent higher in June 2020 than in June 2019 (Berthene 2020). One company noted that its average daily shipping volume rose 21 percent in one quarter of 2020, faster than the company has ever recorded, with a 65-percent increase in shipments to homes (Ziobro 2020).

- **Socioeconomic challenges.** Businesses must overcome challenges to meet customer demands today. These include labor (hiring and retaining staff), unexpected events (increased frequency of disruptive events such as weather), and ability to immediately react to changed conditions.

- **Competitive pressures.** Businesses are finding ways to reduce costs, increase profitability, and gain a competitive edge. Route optimization is one way to make this happen, keeping in mind that routes that do not change to reflect new conditions are inherently not optimal (DispatchTrack 2021).

The pickup and drop-off package industry applies ARO globally every day. These methods produce fast, efficient, and accurate optimized routes in real time and in reaction to change. One global company uses ARO to provide its 55,000 U.S. delivery van drivers the sequence in which they should pick up and deliver packages for the customers assigned to them that day. The direct financial impacts realized by that company included a reduction of 100 million miles driven, with driver-cost avoidance and fuel savings of between $300 and $400 million annually (Holland et al. 2017). Potential non-financial benefits include operators being able to concentrate on driving safely and a reduction in carbon dioxide emissions. ARO is also used in other surface transportation-related businesses, from waste collection to postal deliveries, newspapers, and meter reading.

ARO also enables the airline industry to determine optimal flight paths. Each optimal route depends on the actual conditions for each flight, including forecasted upper air winds and temperatures, the amount of payload, the value of the payload, and the restrictions for the crew and airplane. Not all airlines are using optimized routes. While nearly all computerized flight-planning systems can optimize routes, many airlines still use fixed company routes most of the time. The use of ARO has been limited due to permissions and company policies that place restrictions on routing in certain areas. However, most flight planning systems contain models of all these restrictions, which allows the flight plan to be optimized with dynamic data on winds, temperatures, and costs while still complying with all restrictions. One study of an airline determined that using routes optimized with the most recently forecasted winds, with numerical constraints modeling all requirements, would save about 1 million U.S. gallons of fuel per year. This, in turn, would reduce annual carbon dioxide emissions by about 20 million pounds (Altus 2009).

DESCRIPTION OF POTENTIAL CHANGES

The ARO system will incorporate real-time and historic data in a snowplow routing solution for State and local DOT maintenance and operations to use during adverse winter weather. The solution will support a strategic view for maintenance planning and a tactical view for real-time operations. Dashboards will be provided for users including managers, maintenance supervisors, and drivers.

The ARO system will consider level-of-service goals, route and segment priorities, cycle time expectations, and current and forecast roadway conditions in route optimization. Current (near real-time) conditions to be addressed include atmospheric weather, road weather, incidents, work zones, and traffic volume (or demand). Forecast conditions to be considered will at minimum include weather and road weather conditions, and may include other traffic and operational predictions. Routes will further consider historical crash data, recurring problem areas, and weather-related experience for their routing risk implications. Routing will consider constraints specific to snowplowing operations such as access to fuel and material depots, turnarounds, U-turns, intersection snow clearance, and driver deadheading.

The ARO system will be agnostic with respect to its interfaces with other data systems and systems infrastructure. It will not be tied to a particular application suite or toolkit for implementation. It will use open data specifications drawn from technology standards to the extent that such standards exist and are applicable to its context. It will be able to integrate with existing FHWA and State and local DOT maintenance and operations systems.

Needs and Attributes

The desired characteristics of an ARO system can be enumerated as attributes and needs the system must address. These can be categorized as functional needs, interface needs, performance needs, non-functional needs, system attributes, and system constraints.

Functional Needs

Functional needs describe what the system needs to do or enable users to do. In order to adaptively optimize snowplow routes:

1. The system needs to enable maintenance managers to set maintenance operations objectives (e.g., level of service and cycle time)
2. The system needs to enable maintenance managers to allocate maintenance resources (e.g., vehicles, drivers, depots, materials) for State, county, and municipal agencies:
    a. To and among agency districts
    b. Within districts to and among maintenance sheds or depots
3. The system needs to monitor atmospheric weather conditions (e.g., precipitation type and rates, and temperature)
4. The system needs to monitor traffic conditions (e.g., incidents, work zones, closures, and traffic speeds and volumes)
5. The system needs to assess road weather conditions (e.g., pavement status, pavement temperature, and friction)
6. The system needs to monitor maintenance vehicles in route (i.e., to receive telematics data [e.g., latitude and longitude] from those vehicles)
7. The system needs to optimize routes to changing road weather conditions
8. The system needs to optimize routes to changing traffic conditions
9. The system needs to provide optimized routes to maintenance vehicle drivers in near real-time

Interface Needs

Interface needs describe the interfaces by which the system exchanges information with users and other systems. In order to adaptively optimize snowplow routes:

10. The system needs a means of specifying maintenance operations objectives
11. The system needs a means of specifying the extent of the road network over which routing is to be performed
12. The system needs a means of specifying maintenance resources
13. The system needs sources of atmospheric weather condition information
14. The system needs sources of atmospheric weather condition forecasts (e.g., precipitation type and rates, and temperature)
15. The system needs sources of traffic condition information
16. The system needs sources of historic operations data (e.g., crash data and recurring problem areas)
17. The system needs sources of road weather condition information
18. The system needs sources of road weather condition forecasts (e.g., pavement status, pavement temperature, and friction)
19. The system needs sources of vehicle geo-position information
20. The system needs a means of communicating between the TMC (or the traffic operations center) and the maintenance vehicle
21. The system needs a means of presenting route information to the maintenance vehicle driver (i.e., a driver interface) in near real-time

Performance Needs

Performance needs describe any limitations or constraints on the functions the system is to provide. In order to adaptively optimize snowplow routes:

22. The system needs to provide optimized routes fast enough to be implemented in route

Non-functional Needs

Non-functional needs describe generally desirable attributes of the system. These needs may lead to more explicit requirements as the system is further specified. In order to adaptively optimize snowplow routes:

23. The system needs to be reliable
24. The system needs to implement open data specifications drawn from technology standards, to the extent that such standards exist and are applicable
25. The system needs to be able to integrate with other DOT maintenance and operations systems
26. The system needs to be deployable without excessive customization to accommodate external interfaces
27. The system needs to be flexible to provide deployment options consistent with, for example, agency institutional and contractual arrangements, policies, and resource management schemes

System Attributes

System attributes describes the attributes of the system that may be needed to accommodate other needs. In order to adaptively optimize snowplow routes:

28. The system needs to have secure communications between operations centers and maintenance vehicles
29. The system needs to have sufficient computing power to meet performance needs

System Constraints

System constraints describe limitations placed on the system or its operations by users or other systems. In order to adaptively optimize snowplow routes:

30. The system needs its driver interfaces (need 21) to comply with agency policies for in-vehicle use.

PRIORITIES AMONG CHANGES

Setting priorities among the system needs and attributes can help inform the system development process and decision making. Sponsors, stakeholders, and developers may value some desired features and attributes above others, even when they may be identified as needs. Table 4 identifies the priorities among the system needs and attributes. Needs and attributes are first classed as essential, desirable, or optional; priorities are then set for desirable and optional classifications.

Table 4. Priorities among adaptive route optimization system needs and attributes.

No.	Description	Classification	Priority (1 = lowest, 10 = highest)
1	The system needs to enable maintenance managers to set maintenance operations objectives (e.g., level of service and cycle time).	Essential (E)	Not applicable (N/A)
2a	The system needs to enable maintenance managers to allocate maintenance resources (e.g., vehicles, drivers, depots, materials) for State, county, and municipal agencies to and among agency districts.	E	N/A
2b	The system needs to enable maintenance managers to allocate maintenance resources (e.g., vehicles, drivers, depots, materials) for State, county, and municipal agencies within districts to and among maintenance sheds or depots.	E	N/A
3	The system needs to monitor atmospheric weather conditions (e.g., precipitation type and rates, and temperature).	E	N/A
4	The system needs to monitor traffic conditions (e.g., incidents, work zones, closures, and traffic speeds and volumes).	E	N/A
5	The system needs to assess road weather conditions (e.g., pavement status, pavement temperature, and friction).	E	N/A
6	The system needs to monitor maintenance vehicles in route (i.e., to receive telematics data [e.g., latitude and longitude] from those vehicles).	E	N/A
7	The system needs to optimize routes to changing road weather conditions.	E	N/A
8	The system needs to optimize routes to changing traffic conditions.	E	N/A

Table 4. Priorities among adaptive route optimization system needs and attributes. (continuation)

No.	Description	Classification	Priority (1 = lowest, 10 = highest)
9	The system needs to provide optimized routes to maintenance vehicle drivers in near real-time.	E	N/A
10	The system needs a means of specifying maintenance operations objectives.	E	N/A
11	The system needs a means of specifying the extent of the road network over which routing is to be performed.	E	N/A
12	The system needs a means of specifying maintenance resources.	E	N/A
13	The system needs sources of atmospheric weather condition information.	E	N/A
14	The system needs sources of atmospheric weather condition forecasts (e.g., precipitation type and rates, and temperature).	E	N/A
15	The system needs sources of traffic condition information.	E	N/A
16	The system needs sources of historic operations data (e.g., crash data and recurring problem areas).	Desirable (D)	5
17	The system needs sources of road weather condition information.	E	N/A
18	The system needs sources of road weather condition forecasts (e.g., pavement status, pavement temperature, and friction).	E	N/A
19	The system needs sources of vehicle geo-position information.	E	N/A
20	The system needs a means of communicating between the traffic management (or operations) center and the maintenance vehicle.	E	N/A
21	The system needs a means of presenting route information to the maintenance vehicle driver (i.e., a driver interface) in near real-time.	E	N/A
22	The system needs to provide optimized routes fast enough to be implemented in route.	E	N/A
23	The system needs to be reliable.	E	N/A
24	The system needs to implement open data specifications drawn from technology standards to the extent that such standards exist and are applicable.	D	10

Table 4. Priorities among adaptive route optimization system needs and attributes. (continuation)

No.	Description	Classification	Priority (1 = lowest, 10 = highest)
25	The system needs to be able to integrate with other DOT maintenance and operations systems.	E	N/A
26	The system needs to be deployable without excessive customization to accommodate external interfaces.	D	8
27	The system needs to be flexible to provide deployment options consistent with, for example, agency institutional and contractual arrangements, policies, and resource management schemes.	D	8
28	The system needs to have secure communications between operations centers and maintenance vehicles.	E	N/A
29	The system needs to have sufficient computing power to meet performance needs.	E	N/A
30	The system needs its driver interfaces (need 21) to comply with agency policies for in-vehicle use.	E	N/A

CHANGES CONSIDERED BUT NOT INCLUDED

The following changes were considered but not included:

- ARO is complementary to treatment planning. An ARO system can consider treatment plans in routing, but does not provide road treatment analysis.
- ARO is complementary to asset management. An ARO system does not presume to replicate or replace functions of systems managing roadways or vehicle fleets.
- ARO is complementary to staffing management. An ARO system does not presume to replicate or replace functions of systems managing maintenance and operations personnel.
- ARO uses results of and is complementary to weather and road weather forecasting. An ARO system does not presume to replicate or replace capabilities that might be provided by NWS or a third-party weather service provider.
- ARO uses results of and is complementary to winter road treatment planning. An ARO system does not presume to replicate or replace capabilities that might be provided by a MDSS.
- ARO uses results of and is complementary to traffic monitoring. An ARO system does not presume to replicate or replace capabilities that might be provided by an ATMS or third-party traffic data service.

ASSUMPTIONS AND CONSTRAINTS

ARO is a new, dynamic, and technical capability that builds on work already being done in agencies using simpler methods. Agency staff can benefit from knowing how ARO complements existing efforts, how it will help meet or exceed service goals, and how this meets agency needs. They can benefit from understanding ARO methods and the data needed to apply it to their maintenance activities.

Winter operations management will want assurance that expected ARO benefits and costs are reasonable, sound, and not subject to constant change. They will benefit from being able to communicate the ARO concept and the opportunities it provides. They may be challenged to assure agency leaders that winter operations management understands and is working through institutional deployment challenges for ARO, including sharing data among departments, with other agencies, or establishing computational support internally with information technology staff and resources.

Agency staff will benefit from descriptions of ARO and its deployment, how it helps meet agency goals, and to have opportunities for feedback and modification. Managers will benefit from providing supporting information to address potential staff concerns about job security and autonomy.

ARO will provide routing results to seasonal, new, and experienced drivers. Each group will have different expectations for the system. The system design will need to provide detailed information for less experienced users while allowing for some more experienced operator discretion. A successful implementation will require input from winter maintenance professionals to understand local constraints, testing new routes to identify potential issues, training staff, developing policies, and completing new documentation.

ARO deployment will depend on integrating new data in real time. Aside from selecting the data source, agencies may encounter technical issues with gaining access, working with varied data formats, monitoring reliability, data completeness, and basic availability. Agencies may benefit from modifying or creating data governance plans for managing data sources, updating metadata, and determining data-sharing and data-streaming protocols.

CHAPTER 4. CONCEPTS FOR ADAPTIVE ROUTE OPTIMIZATION

This chapter describes the anticipated future state of ARO for winter maintenance. It describes the background and context for the system only insofar as it differs from the description of the current state in chapter 2. It describes the anticipated ARO system at a high level without specifying the design details.

BACKGROUND, OBJECTIVES, AND SCOPE

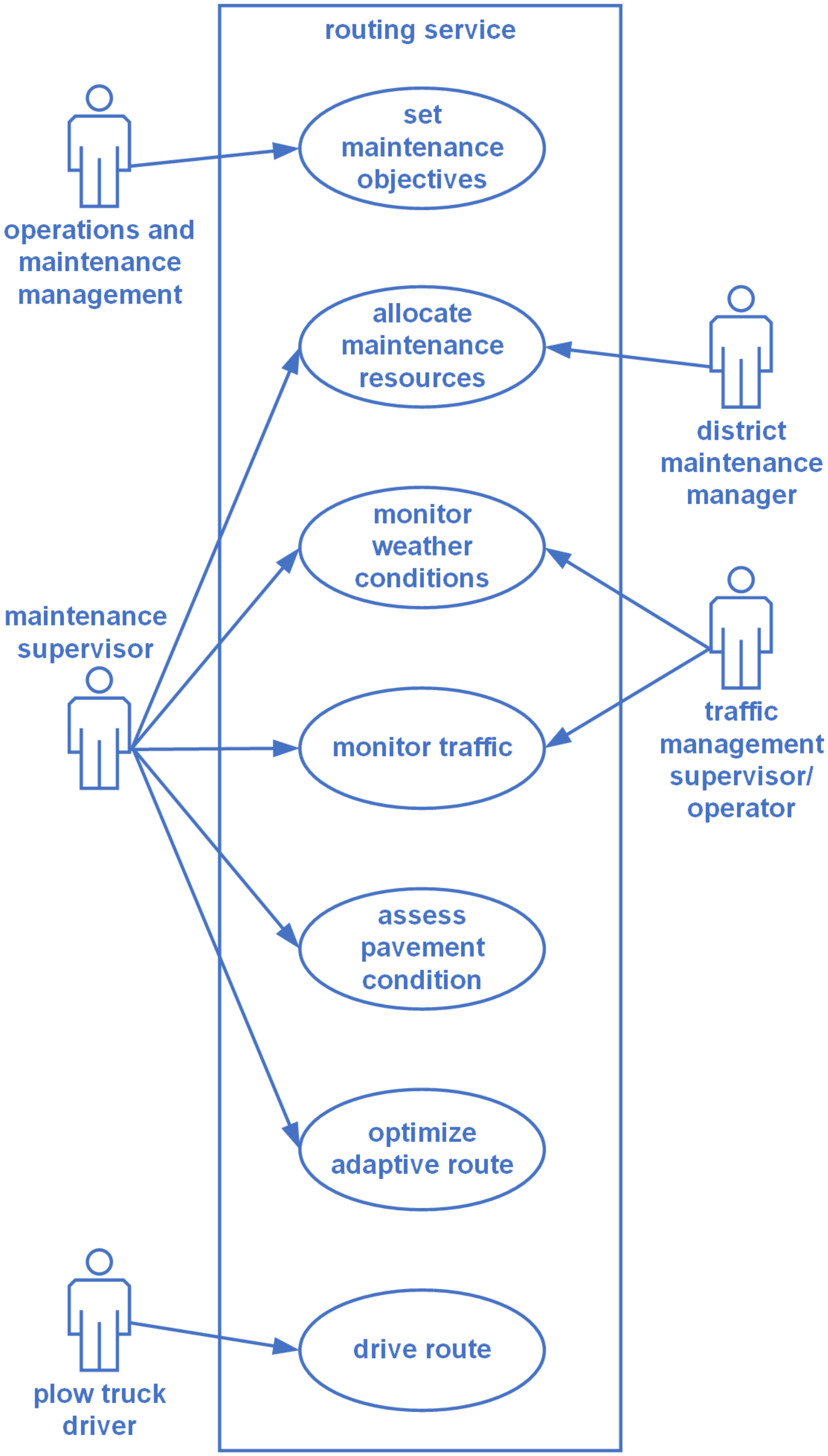
As described in chapter 2, roadway winter maintenance involves complex coordination of activities and resources, from management levels to drivers on the road, over a long season of preparation and execution. The changes described in chapter 3 focus on adaptively optimizing routes, but exchange information with every other winter maintenance process.

Figure 4 illustrates the implied changes relative to the routing use cases in figure 1. Some changes may be apparent:

- A boundary is added to indicate that the scope of a new routing service includes all of the use cases in the diagram.
- The previous "plan route" use case is changed to "optimize adaptive route."
- The routing analyst role, which might have been filled by a maintenance supervisor or subcontractor, is effectively replaced by the routing service.

Changes to each of the use cases may be less apparent in figure 4 but might be important:

- Setting maintenance objectives becomes more dynamic, potentially enabling managers to adapt the extent and timing of treatment and plowing as operational considerations and storms develop.
- Allocating maintenance resources also becomes more dynamic. New information on material stores or shifts in plow truck assignments from one area to another can be implemented dynamically in route plans.
- Monitoring of weather conditions for adaptive routing becomes as important throughout the storm as it was based on forecast before the event.
- Monitoring traffic becomes a proactive factor in adaptive routing rather than just a reactive notification of potential issues.
- Assessing pavement condition becomes available at a fleet and network level rather than just along routes as they are being driven.
- The routing activity has enough information to adapt to changing circumstances across the network so that maintenance can be optimized to meet or exceed objectives.
- Drivers are given explicit routing instructions in real time, adapted to conditions that optimize maintenance across the network, rather than just for their pre-assigned static route.

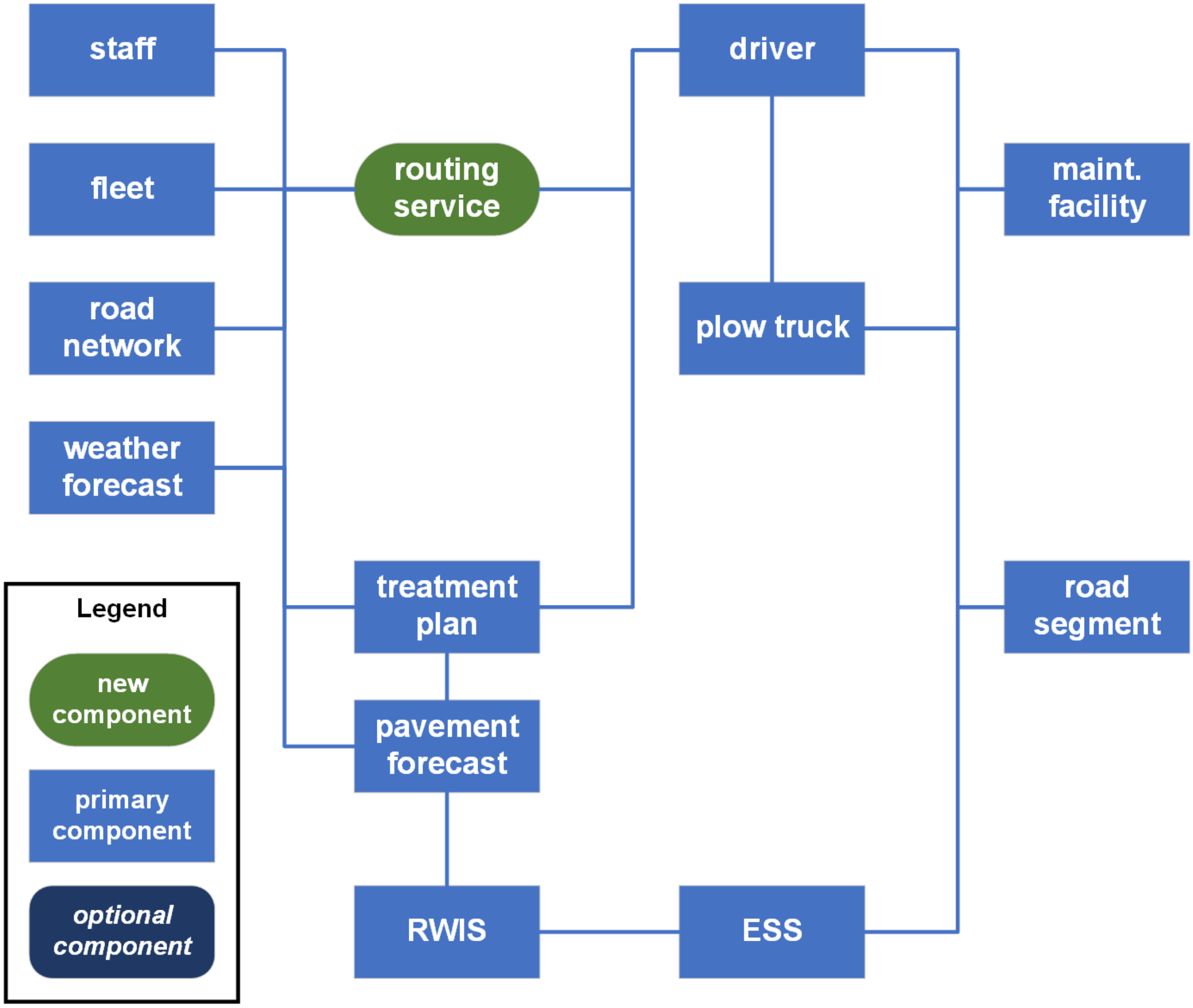


Source: FHWA.

Figure 4. Diagram. Winter maintenance routing use cases with adaptive route optimization.

As illustrated in figure 5, the following components in the winter maintenance context will also change with ARO:

- The routing plan is replaced with a new routing service that dynamically provides optimized route plans adapted to current conditions.
- The pavement forecast, previously an optional component, becomes a primary component of an adaptive optimized solution.



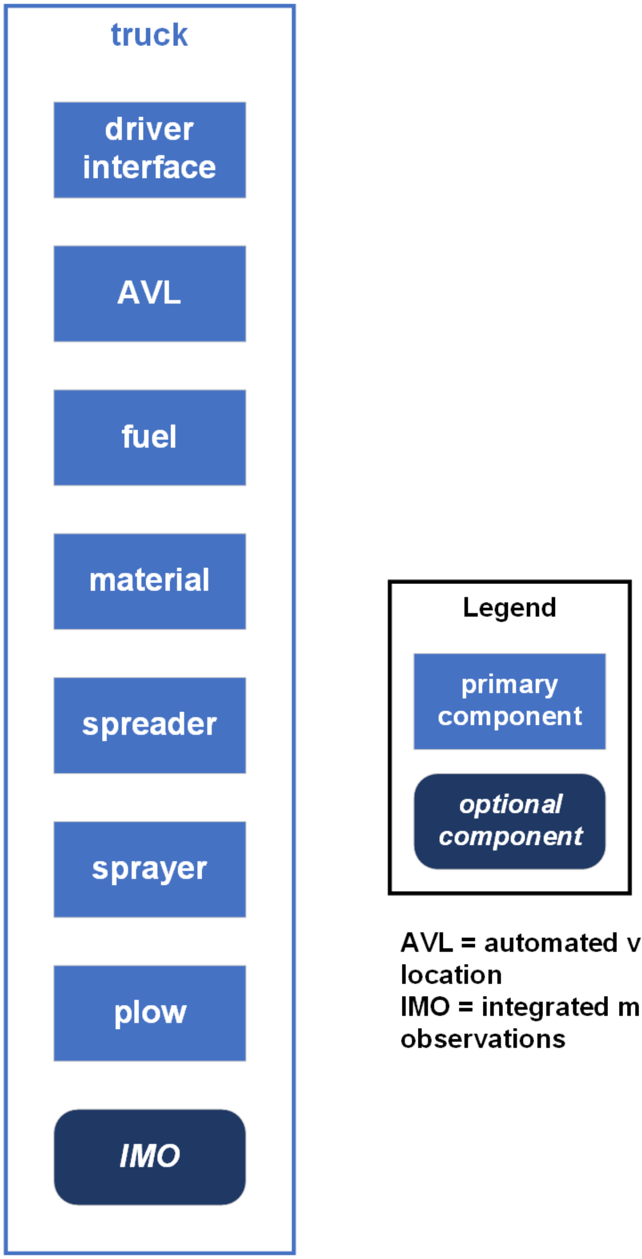
ESS = environmental sensor station. maint. = maintenance.
RWIS = road weather information system.

Source: FHWA.

Figure 5. Diagram. Winter maintenance system components with adaptive route optimization.

As shown in figure 6, the following components in the plow truck are changed to support ARO:

- AVL is needed for ARO to provide dynamic updates of vehicle location and route status.
- A driver interface is needed to provide the updated routes and turn-by-turn recommendations to the drivers.



AVL = automated vehicle location
IMO = integrated mobile observations

Source: FHWA.

Figure 6. Diagram. Winter maintenance system plow truck detail with adaptive route optimization.

STAKEHOLDERS

Figure 4 shows user interactions with the anticipated system. The routing analyst role in current practice is replaced by the new ARO system itself. Other user roles are unchanged, except their interactions with routing activities will be more dynamic throughout a winter maintenance event than they are with static routing.

MODES OF OPERATION

ARO adds a new mode of operation to those that are currently available. Whereas current routes might be pre-planned, even if optimized, ARO adds real-time adaptation that had previously been limited to small changes made by a driver in route. ARO potentially removes restrictions inherent in pre-planned routes. For example, adaptive routes do not need to be associated with a specific "home" maintenance shed. ARO is both optimized and adaptive, providing an online and in-route flexibility for routes across the road network unavailable in the current state of snowplow routing practices.

SYSTEM CONCEPTS

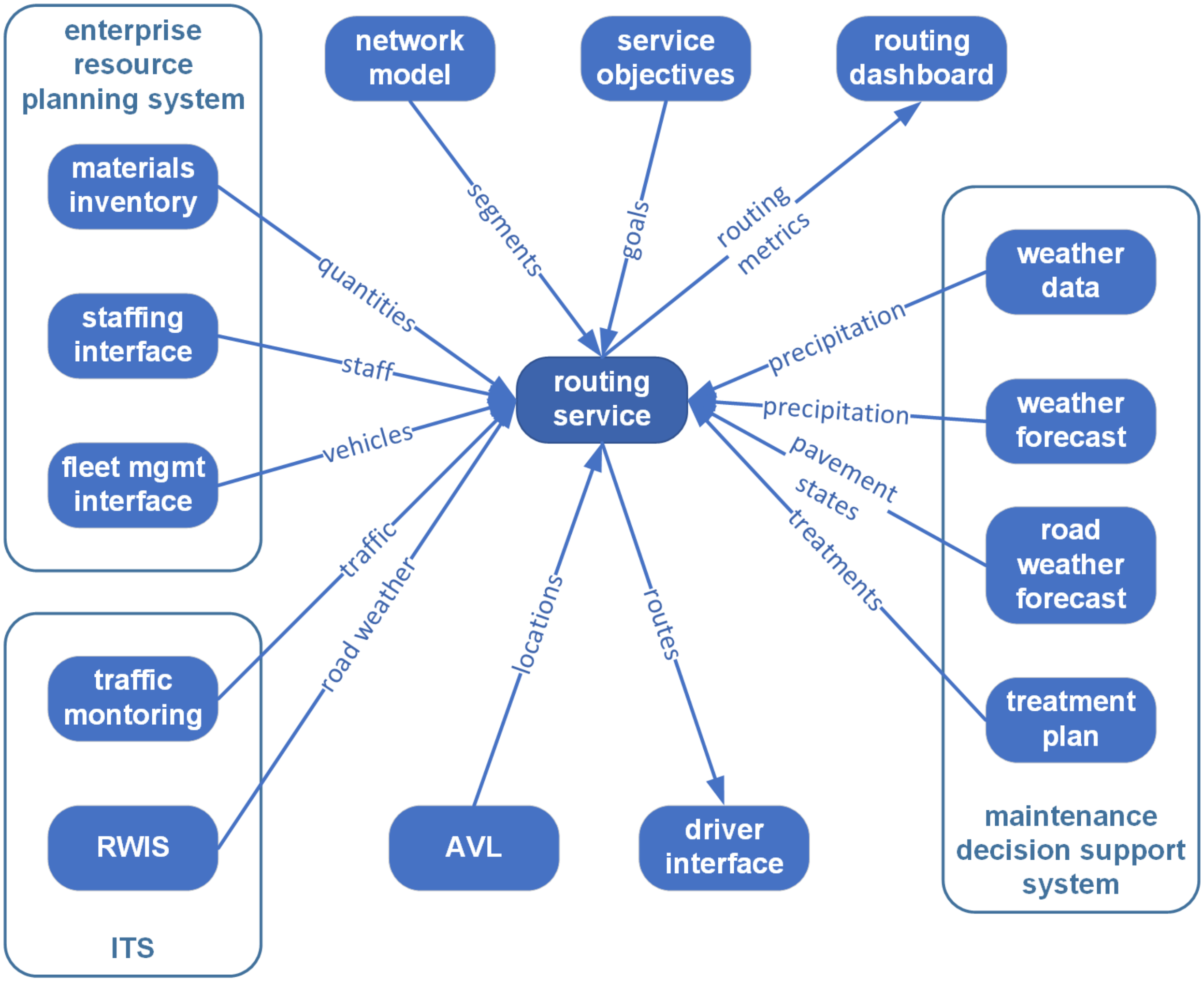
The ARO system will need an array of data sources and interfaces to support its use cases. Figure 7 illustrates the interfaces and flow into the routing service. A road network model is fundamental to enable routing algorithms. The model will include all segments to be treated and plowed and the routable connections between those segments. Connections would include movements through intersections (e.g., through travel, left and right turns, and U-turns), crossovers through medians, and turnarounds.

The service objectives will be specified for sets of segments, perhaps by agency district and road classification. The objectives will enable managers to specify criteria such as maximum time to clearance, pavement state goals, minimum cycle times, and other criteria identified by agency policies.

Material, staff, and equipment resources will be allocated to the routing service as they may be needed to meet the service objectives. Interfaces for resource data might be provided by an enterprise resource planning, maintenance, or asset management system, or through an ARO-specific user interface. Resource information will include:

- Materials inventories at each depot used to determine beginning and resupply points for routes
- Staff availability used to associate and distribute routes from staff locations, typically maintenance sheds
- Fleet and maintenance vehicle availability used to associate vehicles with routes

Traffic data and timely notification of incidents will be included in the ARO calculations. These data will likely come from a real-time interface to an ATMS or a third-party traffic information service. For example, FHWA's Integrated Modeling for Road Condition Prediction system could provide traffic information with weather and road condition data for ARO.



AVL = automated vehicle location. ITS = intelligent transportation system.
RWIS = road weather information system.

Source: FHWA.

Figure 7. Diagram. Interfaces and data flows for adaptive route optimization.

Weather information for ARO includes atmospheric weather data and forecasts, pavement conditions and forecasts, and treatment plans. These may come from independent sources or provided by an MDSS:

- Atmospheric data and forecasts are fundamental in determining needs for and locations of maintenance routes.
- Pavement condition observations and forecasts, generally driven by the weather forecasts, provide higher-resolution ground-level input to determining routing needs.
- Treatment plans relate the routes and the materials needed for treatment by vehicles operating along those routes.

ARO needs information about the locations of maintenance vehicles to determine which segments in the road network have been serviced and to provide starting points for adaptive routing. AVL data fulfill this need. The record of the vehicle path, coupled with information about the in-route treatment, documents the treatment plan implementation. The updated vehicle locations are needed to assess whether events and changing weather conditions warrant ARO from those locations to complete the treatment cycle. AVL systems and interfaces providing those locations may be deployed for IOOs through third-party systems and services.

Optimized adaptive routes will be provided to drivers through a user interface in the vehicle cab. Agency policies and practices will determine the interface form (e.g., hands free, graphical, auditory, head up).

A routing management dashboard will provide performance metrics for routing functions as may be needed for particular user roles:

- Maintenance managers will want to see network maintenance status (e.g., percentage of segments completed) and compare service objectives alongside outcomes (e.g., cycle times and level of service).
- Maintenance supervisors will want to see district and area network status, vehicle utilization, staffing, and material inventories at depots and on vehicles.
- Traffic management supervisors may be monitoring times to speed recovery and levels of service.

SYSTEMS SUPPORT ENVIRONMENT

The systems support environment describes the computing and communications resources needed to support the new system implementation. In many cases, the system attributes are sufficiently well known that specifics about computing platforms, development environments, data storage and management services, and communications services can be identified for the concept.

There is a gap for ARO in understanding what optimization and routing algorithms will be needed. Although system support components are generally identifiable, there is not enough information to describe system capacities (e.g., processors, system memory, storage) or deployment options (e.g., dedicated back office, commercial cloud services). The essential system components will include:

- Processors and memory of sufficient numbers and speed to perform the route optimizations in near real-time, within the routing cycles
- Storage for weather, traffic, and resource data, some of which may be sourced as needed from other system interfaces to be determined
- Communications bandwidth sufficient for near real-time weather, traffic, and resource data flows, and for outbound communications to in-vehicle driver interfaces
- In-vehicle devices for providing driver interfaces to routing instructions

CHAPTER 5. OPERATIONAL SCENARIOS

Scenarios describe how the system should operate under a postulated set of circumstances. This chapter describes three scenarios that highlight particular sets of the system's interfaces and functions.

SCENARIO: SHIFTING RESOURCES

Optimizing snowplow routes with reallocation of plowing resources is a desirable capability for ARO. Such a scenario could develop in the following manner:

- Maintenance and operations leaders gather at the TMC roughly 12 hours prior to a predicted blizzard impacting the State.
- ARO system routing results for the given weather forecast and traffic predictions with baseline snowplow resources (e.g., equipment, personnel, and materials) show that service goals will not be met for this storm for the metro area.
- The weather forecast shows that nearby areas are not going to be hit as hard as the metro. The ARO analysis is re-run with additional plows and personnel shifted to the metro area from bordering areas and facilities.
- Results from ARO analyses show that the metro area and the adjoining maintenance areas will meet their service goals with the resource shift.
- Maintenance and operations leaders approve the shift of resources and the new routes.
- The ARO system sends the approved routes to interface devices in the snowplow trucks, updating the prior route instructions. Operators see the new optimized routing on the driver interface.
- Any further route updates from ARO forecast modeling will append instructions from the current location of the snowplow truck.
- Public information officers and TMC operators monitoring the ARO system dashboard can use its reports to craft public messaging strategies.

This scenario includes the following assumptions and constraints that may affect its success:

- The scenario assumes the ARO system has access to or has received input from maintenance managers about the plow truck and operator resources that would be available from the nearby sheds.
- Snowplow operators would presumably be informed of and trained for the possibility of being routed into a new area. This is not typical of current practices within most State and local DOTs and at most maintenance sheds.
- Sending snowplow operators into a new area with turn-by-turn instructions implies a high level of accuracy in the routing maps. Navigational maps would need to be updated to include all intersection maneuvers allowed for maintenance vehicles, freeway crossovers that may not be shown on maps, and turnaround locations with sufficient space for maintenance vehicles.

SCENARIO: CHANGING WEATHER FORECAST

Forecasting precipitation amounts and types from winter storms is difficult due to the sensitivity of precipitation phase transitions to atmospheric temperature profiles. An ARO system needs to keep up with the changing forecasts, described in the following example:

- The 3–5 day NWS forecast indicates a winter storm with potential for heavy snow will move into the area on Monday morning.
- Maintenance supervisors begin staffing over the weekend according to the most recent ARO analysis before the start of the Monday commute.
- Routing plans for the event are re-optimized with the ARO system based on the updated Sunday 8:00 p.m. forecasts. The routes take into consideration:
    - The geographical extent of storm (which roadways are expected to be treated/plowed)
    - Priority treatment of high-volume interstate highways and thoroughfares
    - The potential for freezing rain prior to changing over to sleet and then snow
    - The increased salt rate needed for freezing rain and the need to return to the depot for more salt before completing even the first cycle of treatment
- Routes are sent to interface devices in the snowplow trucks, from which operators receive turn-by-turn instructions.
- Treatment begins Sunday overnight. Drivers and mobile sensors observe that freezing rain is not materializing and that treatment rate can likely be reduced or halted, depending on whether it is raining.
- The ARO system reassesses optimal routes based on the observed conditions and updated forecasts. The resulting routes reduce the returns to depots and the first cycle treatment times.
- New route instructions are sent to the trucks and drivers.

This scenario includes the following assumptions and constraints that may affect its success:

- The initial routing optimization and the reassessment depend on accurate and timely weather forecasts from NWS or a private weather service provider. The ARO system would need to be configured to monitor and run the new routings whenever a new forecast becomes available.
- Re-running the optimization for observed weather and pavement conditions presumes there are sufficient observed data from mobile (IMO) and fixed sensors (ESS) to characterize conditions apart from the forecasts. An updated weather forecast based on those evolving conditions would also be needed.

SCENARIO: INCIDENT IN ROUTE

Incidents on snowplow routes are not infrequent and can slow storm response. The ARO system can tactically re-optimize routes around these and similar events:

- A snowplow operator is following a prescribed patrol route along Interstate 25 (I–25) north toward Denver. The driver's home shed is at I–25 and Interstate 70, roughly 10 miles north of the driver's current location. The driver is planning to reload materials once there. The vehicle's AVL system sends information about the driver's location and materials inventory to the ARO system.

- A crash occurs on an untreated section of roadway about 3 miles ahead of the driver, preventing the road from being plowed while the incident is cleared and requiring rerouting to continue plowing operations.
    - TMC operators observe the incident and log the location, lanes closed, and estimated clearance time into the ATMS.
    - The vehicle's new route is recomputed with others in the area based on the estimated event clearance time, weather conditions, available material resources on the vehicle, and presence of a queue building upstream from the incident.
- The ARO system sends the new routing plan to the interface device in the operator's truck and to others affected by the incident.
- The interface device notifies the driver of the incident and the new routing. The driver will take the next exit, drive south, and meet up with the patrol near the Monument area on I–25 to join them. The new route expects to plow and treat the incident segment when the incident is cleared and the queue is gone.

This scenario includes the following assumptions and constraints that may affect its success:

- The location of the crash only 3 miles ahead of the snowplow location on its route implies that event detection, re-optimization calculations, and messaging to the snowplow truck's interface device have to be performed within a couple of minutes to reroute the operator before being stuck in the queue.
- Computing the queue length and rerouting through the area once the crash is cleared depend on accurate estimates of traffic conditions and clearance time, both of which are subject to uncertainties.

CHAPTER 6. SUMMARY OF IMPACTS

This chapter describes the potential impacts of the system on operations and organizations, and temporary effects during development and deployment.

OPERATIONAL IMPACTS

Development and deployment of ARO capabilities will rely more heavily on operations data across multiple disciplines than is generally the case in existing routing methods. Data sources and types needed to build and sustain an ARO system include resource/asset management, traffic operations, weather data services, and maintenance operations (e.g., AVL).

ARO capabilities put a premium on real-time operations data. A truly adaptive system will want the best available data to initialize the routing plan, and the data will need to be refreshed as maintenance activities are underway. Broad access to near real-time operations data will enable maintenance planning to become more of a "just-in-time" capability. The risks associated with incomplete data or with premature forecasts are reduced, and the likelihood of meeting or exceeding service goals is increased. Service improvements will then increase customer satisfaction.

From a maintenance management view, improved routing capabilities can lead to more flexibility in staffing and equipment within and among sheds and districts. Maintenance management can more continuously monitor and provide feedback to ongoing activities. Time horizons for management move from being storm-based to being more responsive to events and conditions as they change during a storm. The potential for higher compliance with winter maintenance service objectives could be realized in fewer total miles and driver hours, in more roads cleared quickly, and in treatment material savings.

ORGANIZATIONAL IMPACTS

ARO may have significant organizational impacts within an agency. At management levels, it will potentially drive a tighter coupling between traffic and maintenance operations during winter weather events. This necessitates clear and direct communications but offers benefits to transportations systems management and operations, as well as to maintenance.

A successful ARO deployment may make maintenance organizations rely less on operator experience and familiarity with road network and routes, even while asking operators to be more adaptable to new technologies and methods. This will eventually enable more staffing flexibility as crews become attuned to the processes and depend less on personal knowledge.

It will be key to have buy-in from senior agency management, operations and maintenance leadership, and operators. All stakeholders will need to understand the benefits of ARO. One-on-one peer training has proven to be effective at improving acceptance, although it tends to be a slow process. It may be beneficial to identify a champion, preferably a respected peer, to explain and promote the new technology.

It is generally easier to make changes as new staff and new managers are brought into the organization and its practices. Less experienced drivers may be more adaptable to new technologies. Sometimes, supervisors hired from outside the organization who did not rise up through the ranks can be more open to change. When promoting from within, it may be best to consider people who are willing to embrace new technologies such as ARO.

IMPACTS DURING DEVELOPMENT

Intensive and focused stakeholder information will be needed to overcome the lack of or mixed experience with routing optimization. Even beginning ARO development may be met with skepticism in high-performing organizations that do not necessarily see an immediate need for improvement. On the other hand, organizations with a lack of previous automation experience may be more open to the new systems development effort. The new developments with ARO would not interfere with or be limited by their current systems experience.

In either case, development will require stakeholder involvement in detailing the user needs, design, testing, piloting, and deployment of routing solutions. Real-world testing of optimized routes and driver interactions will need to be phased out to minimize impacts on actual winter maintenance activities.

CHAPTER 7. ANALYSIS

This chapter describes the potential advantages, opportunities, disadvantages, and limitations for ARO system development.

ADVANTAGES AND OPPORTUNITIES

The potential for improved winter maintenance response to storms and inclement conditions is the main advantage of an ARO system. A successful ARO system implementation would lead to faster restoration of clear pavement, safer roadway conditions for the traveling public, and improved mobility under winter driving conditions. As a related benefit, an ARO implementation requires more complete and timely views of operations and winter maintenance activities across the road network. This will improve awareness within and across the transportation agency, and will enable timelier and more effective communications with the public.

Within the agency's operations, ARO can improve human and equipment resource utilization in winter operations. The improved routing could reduce the total route miles and deadheading, which in turn would improve operator satisfaction and morale. Better knowledge of and planning for storm conditions and routing could potentially result in less treatment material usage (relative to non-optimized routes in the absence of an MDSS) and reduced environmental load.

DISADVANTAGES AND LIMITATIONS

Fewer methods and tools are available for solving snowplow routing problems than other routing problems. There are more COTS tools available to solve node-based (pickup and delivery) routing problems than arc-based (or road segment-based) snowplow solutions. Although an ARP may be transformed to a node-routing problem and solved by COTS tools, it might be difficult to incorporate some problem-specific objectives and constraints unique to snowplow operations.

The demand for snowplow route optimization solutions is much less than for pickup and delivery. The pickup and drop-off package industry applies ARO in real time globally every day. These tools produce fast, efficient, and accurate optimized routes in real time and in reaction to change. By contrast, roadway authorities in the United States are not using ARO at all. It is unusual to find an agency that has implemented static route optimization for snowplow operations, let alone adaptive solutions.

There is a gap between static route optimization and ARO. ARO requires identifying and connecting to live data feeds, which trigger route changes based on changed conditions. Once connected, agencies will need to consider what data and trigger points will be used. For the system to be effective, it has to operate in real time. Any latency in receiving dynamic data (e.g., road condition or incident data) will prevent the system from recalculating new routes in a timely manner.

There are few U.S. transportation agency experiences with static or dynamic route optimization applied to snowplow operations. The lack of example and peer implementations may limit the potential to generalize methods and practices. In one example, Colorado DOT network optimization framework did consider recurring problem areas due to weather and historic crash data, but incorporating these data sources required custom software and a base routing network that supports snowplow operations with details including the number of lanes and crossover points.

Academic research focused on the snowplow routing problem is an incomplete body of work. The ideal yet slower problem-independent algorithms (a common tool applied to many locations) cannot meet the computational time requirements of ARO. Using the alternative and much faster problem-specific algorithms requires building the algorithm based on an agency's specific winter maintenance goals and operational constraints. This will complicate applying a common tool among different agencies.

Even a successful deployment of a highly automated system creates new risks of dependency on the automation. Potential for technology outages in data or communications necessitates backup and emergency procedures for operations in case of system failures. Managers and operators have to be trained to multiple levels and methods of response based on system states and capabilities.

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GLOSSARY

adaptative	able to change in response to objectives (for example, cycle times), events (for example, traffic incidents) and changing conditions (for example, precipitation).
atmospheric weather	temperature, precipitation, visibility, and other conditions of the atmosphere above the earth's surface.
automated vehicle location system	a system for monitoring and sending information about a vehicle's location and operating conditions (for example, salt inventory) to an operations center or system.
cycle time	how long it takes to service all lanes of a road segment along a planned route one time.
maintenance depot	a place where supplies and materials (for example, treatment materials) are stored.
maintenance shed	a site for storing and maintaining equipment used for winter maintenance operations.
optimization	techniques or algorithms for finding the optimal solution to a set of objectives (for example, the fastest routes over a set of roadways), subject to a set of constraints (for example, with a limited set of vehicles).
patrol	a group of vehicles (for example, snowplow trucks) operating together to achieve an objective.
road weather	temperature, precipitation condition, slickness or friction, and other conditions on a roadway surface.
route	an ordered set of segments.
segment	a linear link between nodes (intersections) in a network.

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